Extreme wave forces and wave run-up on offshore wind-turbine foundations

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Abstract. *This paper presents studies of wave run-up and wave forces on offshore wind-turbine foundations. The analyses are based on numerical investigations using a Navier-Stokes solver. The free surface is resolved with a Volume of Fluid technique (VOF). Waves approach the foundation from deep water to shallow water over a slope. This initiates breaking for high waves. The breaking process is shown to have a major influence on the run-up and wave forces.*

1 INTRODUCTION

A large number of offshore wind farms are at present under construction. Observations from one of the first farms (which have been installed) have clearly shown that the wave run-up can be quite significant.

Previously, run-up on circular cylinders has been studied experimentally and mathematically. In many cases the main focus has been the total horizontal force and overturning moment, whereas the run-up has been studied in less detail. However, the study by Kriebel (1992) focused on the run-up for periodic waves on a plane bed. The results were compared with 1st and 2nd order analytical wave diffraction theories. 2nd order diffraction theory gave run-up in the order of 50 per cent more than found from 1st order theory, but the experiments gave up to 83 per cent higher than found from 1st order theory. This indicates that the non-linearity of the waves has a large effect on the total run-up. In Büchmann et al. (1998) a second order boundary integral method was used to study run-up on a structure with and without an ambient current. For a small diameter foundation the run-up can be significantly enhanced by the sloping bed in front of the foundation, non-linear wave interaction, and the breaking of the waves as shown in Mase et al. (2001). They set up analytical equations for the run-up, which took wave length, wave height, and slope into account. However, the diameter was not included in their analytical expressions, even though basic diffraction theories show that the diameter has a rather clear effect on the run-up.

Chan et al. (1995) studied the run-up and especially the forces on a circular cylinder under the influence of a plunging breaker. From that study it is clear that the breaking process has great impact on the maximum horizontal forces. By examining photographs from the experiments the breaking process is found to influence the run-up as well. Wienke et al. (2000), and Wienke and Oumeraci H.(2005) also found that the breaking process is very important when studying the maximum forces on slender piles. They studied especially the slamming process, which for extreme waves gives the largest contribution to the maximum horizontal force. The breaking waves were controlled with a Gaussian Wave packet. The wave packet converges to a point of concentration and eventually breaks. A theory for the slamming force was elaborated, where it was assumed that outside the slamming area the wave force could be found using Morisons equation.

In a natural sea a number of phenomena can cause wave breaking. The wave breaking may be caused by the presence of the windmill itself, by the bed slope leading to shallow water, unstable wave kinematics, three-dimensional wave interactions, and perhaps also effect from current and wind.

This paper presents results from numerical simulations of wave run-up and wave forces on wind-turbine foundations. The focus has been the effect of breaking waves. The wave breaking is generated by the slope in front of the circular cylinder. The incoming waves are regular. The paper is organised as follows; Chapter 2 describes the numerical method, Chapter 3 the test cases and dimension analyses. Chapter 4 shows the results and finally Chapter 5 summarizes the conclusions.

2 NUMERICAL METHOD

The Navier-Stokes equations in three dimensions are solved using a finite-volume approach on a multi-block grid. The viscous forces are in the present study neglected, which reduces the Navier-Stokes to the Euler equations, which is given below.

$$\frac{\partial u_i}{\partial x_i} = 0$$
$$\rho \frac{\partial u_i}{\partial t} + \rho \frac{\partial u_i u_j}{\partial x_j} = \rho g_i - \frac{\partial p}{\partial x_i} \qquad (1)$$

The u_i are the three velocity components, g the gravitational acceleration, p is the pressure, and ρ the fluid density.

The free surface geometry is governed by the kinematic boundary condition where a particle on the free surface follows the local fluid velocity. The kinematic boundary condition is included by extrapolation of the velocities within the fluid domain to the surface and through the use of the Volume of Fluid method discussed later.

The dynamic boundary condition in the case of an invicid fluid is given as:

$$p_{surf} = p_{atm} \qquad (2)$$

The atmospheric pressure is set to zero, and instead of solving for the pressure itself the mean hydrostatic pressure is taken out of the equation. The equation is reformulated using the excess pressure so the dynamic condition for the free surface becomes:

$$\tilde{p}_{surf} = g_i r_i \tag{3}$$

where r_i is the position of the surface given as a vector.

The spatial discretisation is based on the finite-volume approach on a multi-block grid. The time integration of the Navier-Stokes equations is performed by application of the fractional step method. Fig. 1 shows an example of the multi-block grid used for the study of run-up on wind-turbine foundations. The grid consists of 12 blocks.

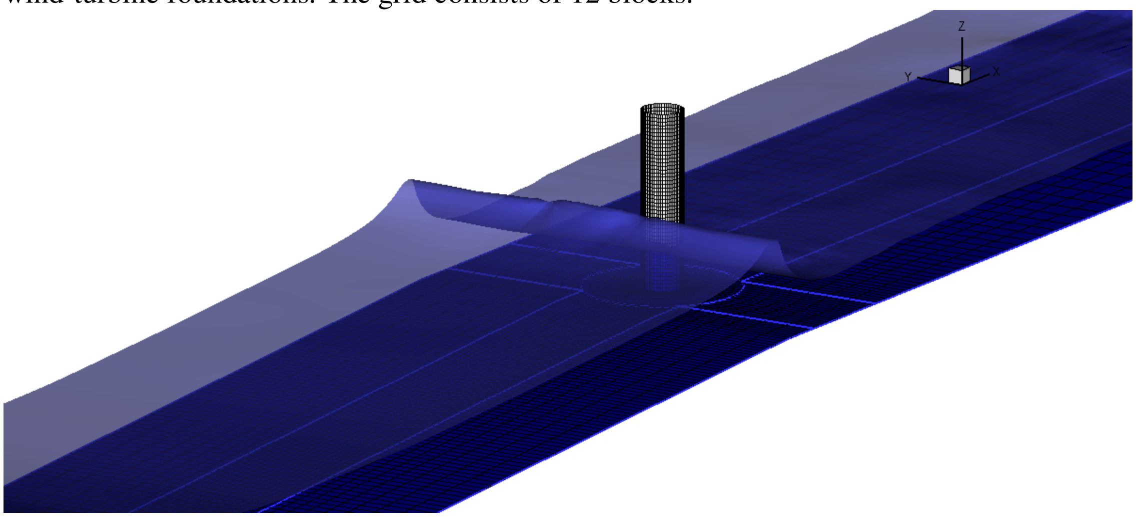

Figure 1: The multi-block structure of the computational domain shown at the bed(thick blue lines). The grid consists of twelve 3D blocks of structured data cells.

The free surface is resolved using a Volume-of-Fluid (VOF) description, with an improved scheme for the advection of the conservative quantity, F, cf. Ubbink (1997). The grid is fixed, while the conservative quantity, F, moves with the fluid. F is assigned a value of 1 within the fluid domain and 0 in the void domain (the effect of air is not included). F = 0.5 determines the position of the surface

The waves are generated at an inlet boundary where Stokes waves up to 5th order, cnoidal waves up to 5th order, or stream function waves can be specified. At the down-wave end the wave energy is absorbed by means of a sponge layer, so wave reflection is minimised.

The CFD-code solving the Navier-Stokes equations as sketched above has been used and validated in Nielsen and Mayer (2001), and Christensen et al. (2004).

The total force on the circular cylinder is found by integrating the total pressure around the cylinder. Hereby any frictional forces are neglected.

3 TEST CASES

The number of simulations is altogether 32. Two of these are comparisons tests related to the comparison with the experimental data reported in Kriebel (1992), and Kriebel (1998), Sensitivity tests of the run-up to the grid resolution was made in Christensen and Hansen

(2005). The rest is tests that will elucidate the influence of the slope (or the surf similarity parameter), the wave height, and the diameter of the cylinder, on the run-up and horizontal force on the cylinder.

The run-up and force depend on a number of parameters. In the following only two-dimensional regular period incoming waves and constant slope are considered. With these limitations the following generic relationship can be written

$$R = f_r(H_0, T, L_0, g, \beta, h, D, \nu) \tag{4}$$

$$F = f_f(H_0, T, L_0, g, \beta, h, D, \rho, \nu) \tag{5}$$

where H_0 is the deep water wave height, T the wave period, L_0 the deep water wave length, g the gravitational acceleration, β the slope, h the water depth, D the diameter of the foundation cylinder, ν the kinematic viscosity, and ρ the density of the water .

In coastal areas the bed slope is often incorporated through the surf similarity parameter defined as $\xi_0 = tan(\beta) / \sqrt{H_0 / L_0}$, where β is the bed slope given in degrees. For linear wave theory the wave length is entirely determined by the depth and wave period. Therefore either T or L_0 can be neglected in the dimension analyses. The depth is used as length scale, while $\sqrt{h/g}$ is used as time scale. The dimensionless run-up is

$$R / h = f(H_0 / h, T / \sqrt{h/g}, \xi_0, D / h, Re) \tag{6}$$

$$F /(\rho g h^3) = f(H_0 / h, T / \sqrt{h/g}, \xi_0, D / h, Re) \tag{7}$$

This gives altogether five parameters, which are the dimensionless [a)]wave height, [b)]wave period, [c)]surf similarity parameter, [d)]diameter, and [e)]Reynolds number. The analyses in Mase et al. (2001) included the first three parameters but they did not include the dimensionless diameter of the circular cylinder. In many analyses of diffraction around vertical circular cylinders the bed is plane and therefore the run-up only depends on three parameters; the wave height, wave number (or the period), and the diameter, see Kriebel (1992), and for large cylinders viscosity can often be neglected. For wind turbine foundations with a diameter of around 4 to 5 meters the drag force part of the total force, which depends on the viscosity (and turbulence), might be of some importance but is not studied in detail in this study.

The standard formulation of the dimensionless horizontal force in diffraction theory is based on the radius of the vertical circular cylinder ½D, the water depth h and the wave height as follows:

$$F /(\tfrac{1}{2} \rho g D h H_0 (tanh(kh) / kh)) = f(H_0 / h, T / \sqrt{h/g}, \xi_0, D / h, Re) \tag{8}$$

3.1 Cylinder on a horizontal plane bed

Two calculations are made for comparison with the experiments referenced in Table 1. The test cases are used to validate the numerical approach described in Section 2. The experimental data are found in Kriebel (1992) and Kriebel (1998). In one of the cases a comparison of the run-up is made, while a comparison for the horizontal force is made for the other.

Test no.	kD/2	kh	kH	D (m)	H (m)	h (m)	L (m)	Δt (s)	No. Cells
K1	0.374	1.036	0.205	4.0	1.096	5.54	33.6	0.010	299008
K2	0.374	1.036	0.286	4.0	1.529	5.54	33.6	0.010	299008

Table 1 : Test examples for comparison with experiments reported in Kriebel (1992) K1, and Kriebel (1998) K2.

3.2 Cylinder on a sloping bed

In Eqs (6) the dimensionless run-up has been found to depend on five parameters. In this study three of these are investigated. They are the dimensionless wave height and diameter, and the surf similarity parameter. The remaining variable is the dimensionless wave period, and Reynolds number. For large diameter cylinders Reynolds effects in waves can be neglected.

The dimensionless wave height, H_0/h, varies from 0.167 to 1, the surf similarity parameter, ξ_0, from 0.15 to 0.4, and finally the dimensionless diameter, D/h, was either 0.667 or 1.33.

4 RESULTS

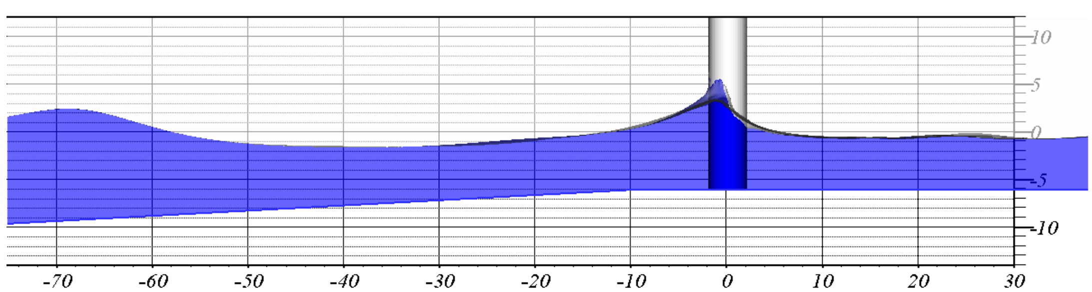

Figure 2: An example of the run-up for a case with sloping bed in front of the vertical circular cylinder.

An example of the calculation of the run-up is shown in Fig. 2. In this case the diameter is 4 m, the water depth is 6 m, the slope is 1:20, the wave period T = 7.73 s and the deep water wave height is 4 m. This gives the following dimensionless variables: H_0/h = 0.667, D/h= 0.667, and ξ_0 = 0.24. It is clear that the run-up is larger than the wave height. If the run-up is made dimensionless as in Kriebel (1992) with half the wave height, we find that $2R/H_0$ is in the order of 2.75. This is very high compared to the run-up observed in Kribel (1992), where the maximum run-up, $2R/H_0$, was smaller than 2.5 except for one extreme case. The maximum run-up for the extreme case in Kriebel (1992) was found for $kD/2$= 0.917, while it is 0.27 in this case.

4.1 Comparison with the experiments in Kriebel (1992) and Kriebel (1998)

A comparison of the run-up for two cases is shown in Fig. 3. The front of the cylinder is located at β/π =0, and the back of the cylinder at β/π =0. The calculated run-up around the cylinder in Fig. 3 shows a very good agreement with the observed maximum run-up when the Navier-Stokes solver is used. Compared to results from 1st and 2nd order wave diffraction theories, the Navier-Stokes solver predicts the run-up more accurately. Only at the front of the cylinder the run-up is slightly underestimated.

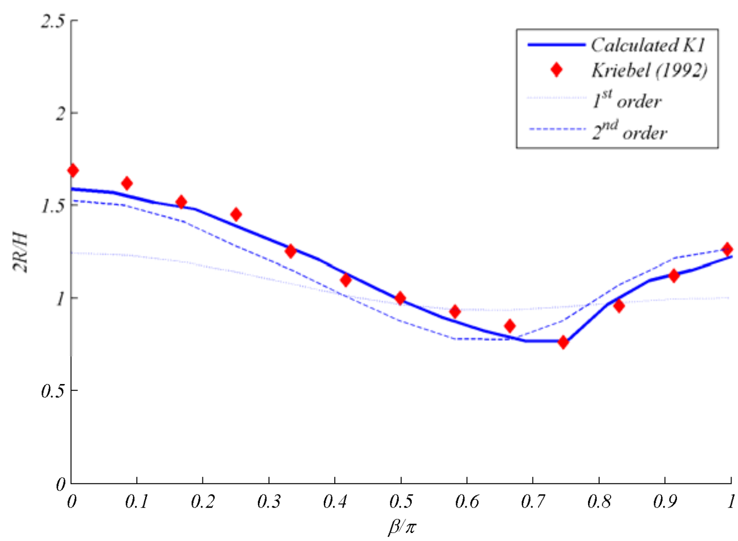

Figure 3: Comparison between observed run-up (diamonds), and the calculated run-up, (full line) for case K1, while the other two line are found from 1st and 2nd order diffraction theory.

Fig 4 shows and example of the horizontal force on the cylinder compared to measurements from Kriebel (1998). The force has been made dimensionless with $F_0 = ½\rho g D h H_0 (tanh(kh)/kh)$. The maximum force on the cylinder is well predicted with NS3. It is clear that the asymmetry is well captured by the model.

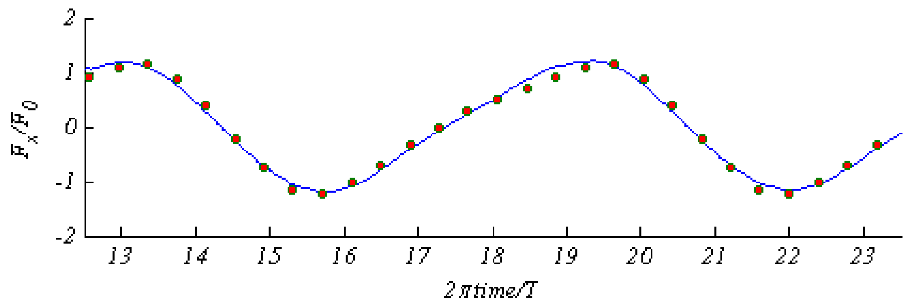

Figure 4: Comparison of the calculated horizontal force (full line) to measurements from Kriebel (1998) (dots).

4.2 Run-up on a vertical cylinder on a sloping bed

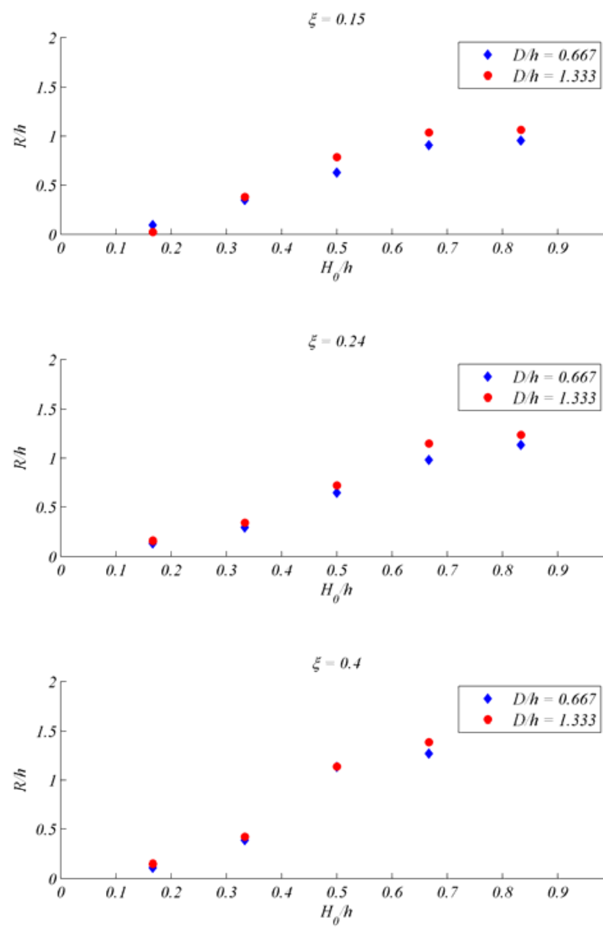

Figure 5: Dimensionless run-up as a function of the dimensionless deep water wave height.

For 30 cases the maximum run-up at the front of the vertical cylinder has been shown in Fig. 5. The dimensionless run-up, *R/h,* has been depicted as a function of the dimensionless wave height, *H_0/h.* The three panels show the run-up for three different values of the surf similarity parameter. The surf similarity parameter governs the shoaling and breaking process over the sloping bed.

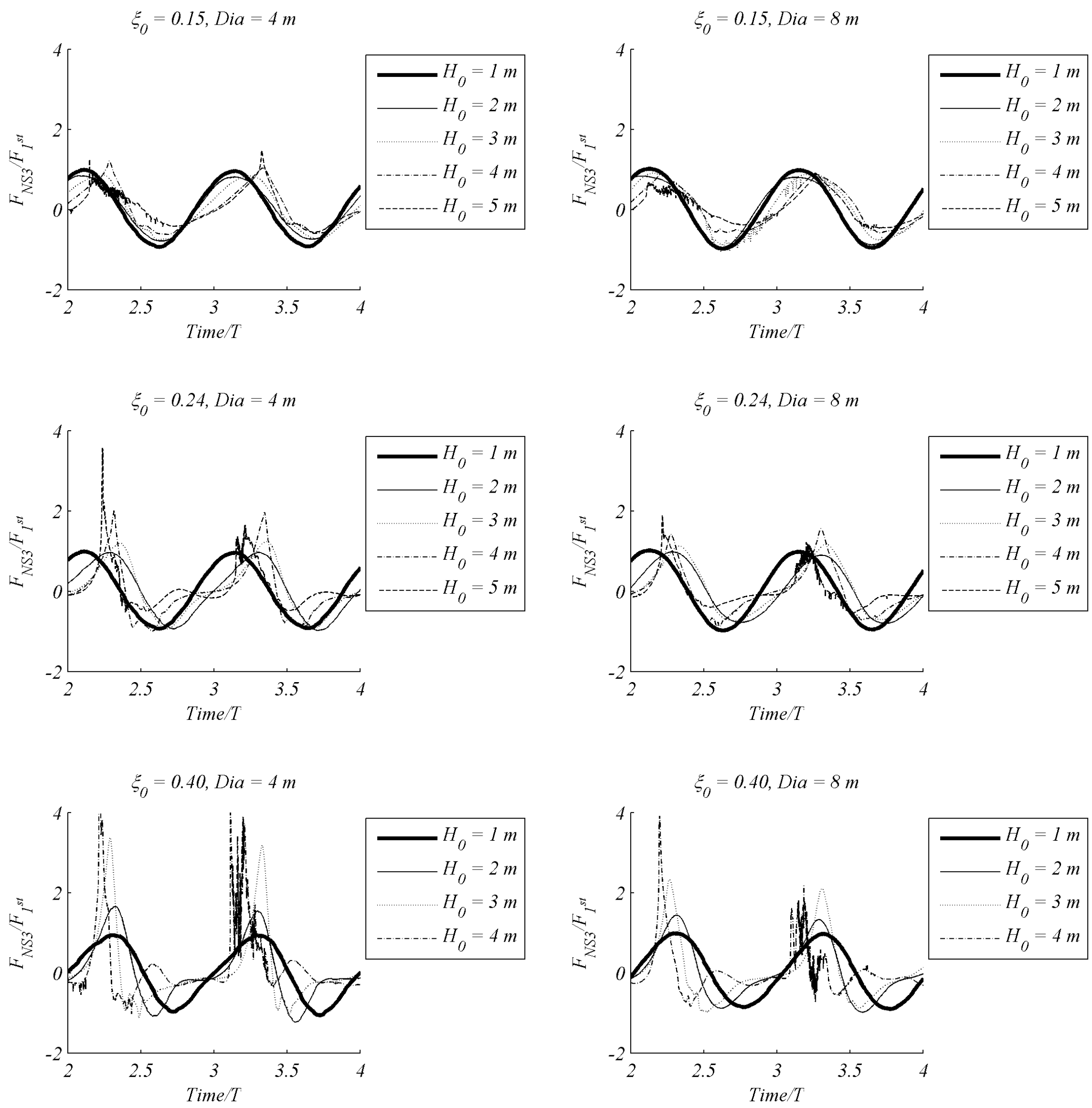

Figure 6: The horizontal force made dimensionless with the 1st order horizontal force found form potential diffraction theory.

For small values the waves break as spilling breakers, while a plunging breaker is generated for larger values. For the dimensionless wave height, H_0/h = 0.667, the run-up increases by 33 per cent, when ξ_0 increases from 0.15 to 0.4. Increasing the diameter from D/h = 0.667 to 1.333 gives an increase of the run-up in the order of 10 to 15 per cent. The run-up seems to have a maximum for $H_0/h \approx 0.8$. This means that the largest run-up is found when the wave is just about to break.

In fig 6 time-series of the horizontal force on the cylinder for the 30 cases are shown. The horizontal force has been made dimensionless with the force found from linear diffraction theory, where the wave height at center at the vertical cylinder has been used found by linear shoaling. It is quite clear that the force on the cylinder becomes more peaked as the surf similarity parameter increases, which indicates an increase in the peak force when the breaking of the wave goes from a spilling type to a plunging type.

For the small wave heights , ie. H_0 = 1 m, a good agreement is found for the maximum force with linear diffraction theory (1st order), see Fig 7. For higher waves the difference is at least up to a factor 4 larger.

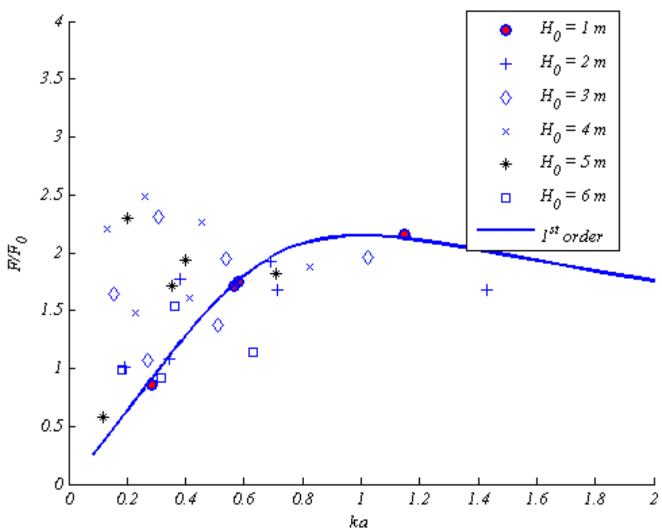

Figure 7: Comparison between the calculated horizontal force and linear diffraction theory, for a Dia. = 4 m.

5 SUMMARY AND CONCLUSIONS

The wave run-up and horizontal wave force on a vertical circular cylinder has been investigated by a Navier-Stokes solver. In all the test cases the incoming waves are two-dimensional and regular. Initially, two test cases are used to validate the method with moderate non-linear wave height. The comparison shows good agreement.

It is clear that the run-up caused by nearly breaking/unstable waves is much higher than for run-up for stable periodic waves. An increase of the surf similarity parameter from 0.15 to 0.4 results in an increase of the run-up in the order of 33 per cent. When the diameter is increased from D/h = 0.667 to D/h = 1.333 an increase in the run-up is in the order of 10 to 15 per cent. The maximum run-up is found for $H_0/h \approx 0.8$. This indicates that the run-up is higher when the wave is just about to break compared to the fully broken wave.

The peak horizontal force depends to a high degree on the breaker type. The peak horizontal force is significantly increased when going from a spilling to a plunging breaker.

Several aspects should be investigated in more detail, such as the distance from the slope to the vertical cylinder, effect of irregular waves in the full three-dimensional sea, a different shape of the foundation. The sensitivity of the results to the grid resolution should also be investigated. It should be noted that for relatively high but not breaking waves an excellent agreement to measurements have already been achieved.

Acknowledgement

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